Appendix 2

Columnar Aerosol Properties Over Oceans by Combining Surface and Aircraft Measurements: Simulations

by

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Abstract

We report an algorithm that can be used to invert the radiance exiting the top and bottom of the atmosphere to yield the columnar optical properties of the atmospheric aerosol under clear sky conditions over the oceans. The method is an augmentation of a similar algorithm presented by Wang and Gordon [*Appl. Opt.*, **32**, 4598–4609 (1993)] that only utilized sky radiance, and therefore, was incapable of retrieving the aerosol phase function at the large scattering angles that are of critical importance in remote sensing oceanic and atmospheric properties with satellites. Well known aerosol models were combined with radiative transfer theory to simulate pseudodata for testing the algorithm. The tests suggest that it should be possible to retrieve the aerosol phase function and the aerosol single scattering albedo accurately over the visible spectrum at aerosol optical thicknesses as large as 2.0. The algorithm is capable of retrievals with such large optical thicknesses because all significant orders of multiple scattering are included. We believe that combining an algorithm of this type with surface-based and high altitude aircraft-based radiance measurements could be useful for studying aerosol columnar optical properties over oceans and large lakes. The retrieval method is possible over the oceans because, unlike the land surface, its albedo is low and spatially uniform.

1. Introduction

In a recent paper, Wang and Gordon[1] reported an algorithm for retrieval of the aerosol phase function, $P(\Theta)$, where Θ is the scattering angle, and the aerosol single scattering albedo, ω_0, from measurements of the aerosol optical thickness, τ_a, and the normalized sky radiance, $\rho_t(\hat{\xi}_i)$, where $\hat{\xi}_i$ is a unit vector corresponding to the i^{th} direction in which the measured radiance is propagating, over the oceans. The normalized radiance ρ corresponding to the actual radiance L (mW/cm$^2\mu$m Sr) is defined by $\pi L/F_0 \cos\theta_0$, where θ_0 is the solar zenith angle and F_0 is the extraterrestrial solar irradiance (mW/cm$^2\mu$m). The retrieval algorithm, an extension of earlier work by King,[2] Box and Deepak,[3,4] Nakajima et al.,[5] and Wendisch and von Hoynunegn-Huene,[6] included all significant orders of multiple scattering and, therefore, was not limited to small values of τ_a. The retrieval method is possible over the oceans because, unlike the land surface, its albedo is low and nearly spatially uniform.

The basic idea of the algorithm is to find aerosol properties that, when inserted into the radiative transfer equation (RTE), yield the measured values of $\rho_t(\hat{\xi})$. Briefly, from initial guesses for ω_0 and $P(\Theta)$, the RTE was solved using the given (measured) value of τ_a to find the predicted sky radiance. The differences $\Delta\rho(\hat{\xi}_i)$ between the predicted and measured sky radiances were then used to provide a new phase function and ω_0. This was accomplished using the single scattering approximation in the following manner. First, the scattering angle Θ_i that would be appropriate to the single scattering of incident solar radiation in the direction $\hat{\xi}_i$ is determined for each point at which the sky radiance is measured, i.e., each $\hat{\xi}_i$. Then the error in the computed sky radiance is used to estimate the error $\Delta[\omega_0 P(\Theta_i)]$ in the trial value of $\omega_0 P(\Theta_i)$ using the appropriate single scattering formulas. The value of $\omega_0 P(\Theta_i)$ is then changed by a fraction (usually 0.5) of $\Delta[\omega_0 P(\Theta_i)]$ yielding a revised value. The revised $\omega_0 P(\Theta_i)$ is then inserted into the RTE and new values of $\rho_t(\hat{\xi}_i)$ are computed. Finally, the process is repeated until the measured and computed $\rho_t(\hat{\xi}_i)$ are in agreement within the experimental error. Using simulated pseudodata, Wang and Gordon[1] found that the rms error between the measured and computed $\rho_t(\hat{\xi}_i)$'s could usually be reduced to a fraction of 1%. Clearly, there are scattering angles Θ that are unaccessible with this procedure, i.e., the maximum value of Θ is $\Theta_{max} = \pi/2 + \theta_0$, where θ_0 is the solar zenith angle. Thus, there is no way to derive $P(\Theta)$ for $\Theta > \Theta_{max}$. For these angles, Wang and Gordon[1] simply made a guess for P, e.g., $P(\Theta) = P(\Theta_{max})$ for $\Theta > \Theta_{max}$. The guess enables derivation of ω_0 from $\omega_0 P(\Theta)$ by integration over solid angle. Through simulations it was found that excellent values of ω_0 and $P(\Theta)$, for $\Theta < \Theta_{max}$, could be retrieved using these ideas. Note that this approach provides a full multiple scattering inversion of the sky radiance; the single scattering formulas are used *only* to provide the direction (increase or decrease), and a coarse estimate of the amount, that $\omega_0 P(\Theta)$ should be changed at each step of the iteration.

One goal in developing this algorithm was to provide a means of supplying aerosol optical properties for vicarious calibration of spaceborne sensors viewing the ocean in the visible and near infrared regions of the spectrum.[7–10] However, the fact that $P(\Theta)$ cannot be determined for $\Theta > \pi/2 + \theta_0$, a range of angles of critical importance in deriving the expected radiance at the sensor, limits the utility of the method for this application. Thus, we have examined the possibility of combining surface and aircraft data to determine remotely the columnar phase function over the full angular range. In this note, we report that such a combination has the potential for providing excellent retrievals of $P(\Theta)$ and ω_0. In a later paper, we will provide a full sensitivity analysis to determine the limitations of the method.

2. Inversion algorithm

The algorithm for combining the surface and aircraft radiance distributions is similar to that developed by Wang and Gordon[1] with three differences. First, the complex initial guess procedure for $P(\Theta)$ and ω_0 they described was replaced by the assumption of a two-term Henyey-Greenstein phase function with $\omega_0 = 1$, as it was found that the initial guesses for these quantities was not critical. Second, in the case of the TOA radiances, the contribution from Rayleigh scattering does not have to propagate through the aerosol layer, so Eqs. (5), (8), and (9) of Ref. 1 were modified by removing the exponential factor. Finally, spline interpolation on $\log[\omega_0 P(\Theta)]$ was used to provide $\omega_0 P(\Theta)$ between the retrieved values, and $\omega_0 P(\Theta)$ was extrapolated to $\Theta = 0$ by fitting $\log[\omega_0 P(\Theta)]$ for the four smallest values of Θ to a quadratic function in Θ using least squares.

3. Simulated Inversions

To test the algorithm, we have used the Shettle and Fenn[11] Maritime aerosol model with a relative humidity (RH) of 99% and their Urban model with RH = 0. The Maritime model is the more demanding test, as the phase function is more strongly peaked in the forward direction and shows significant variability near the rainbow angle ($\sim 140°$). The Urban model on the other hand has strong absorption ($\omega_0 \sim 0.6$) and provides a test of the algorithm's ability to retrieve ω_0 in such cases. The radiance, exiting the top of the atmosphere (TOA) and incident on the sea surface, was computed using a two-layer successive order of scattering radiative transfer code[1] with the aerosols in the lower layer and the molecular scattering component in the upper layer. This should be a good approximation to the vertical structure of the atmosphere over the oceans in situations in which the aerosol is locally generated and confined to the marine boundary layer. The surface radiance in the solar almucantar and principal plane, and the TOA radiance in the principal plane, computed in this manner, were used as pseudodata to test the retrieval algorithm. It is important to note, that in the radiative transfer code used in the inversion iteration procedure, the assumed vertical structure of the aerosol is the same as for that used in the generation of the pseudodata, i.e., the correct vertical structure, as might be determined from lidar measurements, was used in the retrieval algorithm.

In applying the algorithm to the pseudodata, we found it was very important not to include both surface and TOA radiances with similar values of Θ_i, which we call redundant data. The reason for this is that the multiple scattering effects in redundant data sets can be significantly different. This slows down convergence of the algorithm. Therefore, the surface almucantar was used for $0 \le \Theta_i \le 2\theta_0$, the surface principal plane for $2\theta_0 < \Theta_i < \pi/2 + \theta_0$, and the TOA in the principal plane for $\Theta_i > \pi/2 + \theta_0$. This was similar to the surface data used in Wang and Gordon.[1] Note that no redundant data was utilized. In the tests described below, the pseudodata density used in the retrievals was as follows: (1) in the aureole region of the almucantar the pseudodata were used in 1° increments of azimuth from the sun (ϕ) from $\phi = 1°$ to 15°; (2) in the remainder of the almucantar, the pseudodata were spaced in 5°increments; (3) in the principal plane, the surface pseudodata were used in $\sim 3°$ increments in viewing angle (θ_v, the polar angle associated with $\hat{\xi}_i$)

in enough directions to fill $2\theta_0 < \Theta_i < \pi/2 + \theta_0$ (with $\theta_v < 86°$); and at the TOA in the principal plane the pseudodata were employed in $\sim 7°$ increments in viewing angle in enough directions to fill the region $\Theta_i > \pi/2 + \theta_0$. For $\theta_0 = 60°$, this sampling provided ρ_t at the surface in 63 directions and at the TOA in 7 directions.

Samples of the retrievals for the Maritime aerosol model with $\theta_0 = 60°$ are provided in Figure 1, which compares the retrieved $\omega_0 P(\Theta)$ [circles] and the true $\omega_0 P(\Theta)$ [line] as a function of Θ, and Figure 2 which provides the % error in the retrieved values of $\omega_0 P(\Theta)$. Figures 1a and 2a are for 412 nm, while Figures 1b and 2b are for 865 nm. At 865 nm the contribution to ρ_t from Rayleigh scattering is small because the Rayleigh optical thickness, τ_r, is only ~ 0.015. In contrast, at 412 nm the Rayleigh contribution is significant as $\tau_r \approx 0.32$. Two aerosol optical thicknesses (τ_a) were examined, 0.2 and 2.0, corresponding to a relatively clear and a very turbid atmosphere, respectively.

At 865 nm the algorithm retrieves $\omega_0 P(\Theta)$ and ω_0 were excellent using 60 and 120 iterations for $\tau_a = 0.2$ and 2.0, respectively. The maximum error in $\omega_0 P(\Theta)$ was $\sim 3.5\%$ near the rainbow angle and $\lesssim 1\%$ elsewhere. We computed the average (over i) of the absolute value of the relative difference between $\rho_t^{(c)}$, the radiances computed from the retrieved $\omega_0 P(\Theta)$, and the original (measured) values of ρ_t. By this measure, the error in the radiance using the retrieved $\omega_0 P(\Theta)$ was a small fraction (< 0.1) of 1%.

At 412 nm the retrieval accuracy is also excellent for the smaller τ_a, for which the error in $\omega_0 P(\Theta)$ was usually $\lesssim 1.5\%$; however, for $\tau_a = 2.0$, even with 300 iterations, the retrieval is not as good, particularly in the vicinity of the rainbow angle, where the phase function changes rapidly with Θ (maximum error in $\omega_0 P(\Theta) \lesssim 10\%$). Multiple scattering smooths the rapid variations in radiance with ξ_i that are observed near the single scattering limit, and this reduces the efficacy of the algorithm near the rainbow angle. Somewhat better retrievals were obtained through the rainbow region in this case by substituting TOA psuedodata in place of the surface principal plane pseudodata. Presumably this occurs because the TOA radiances corresponding to scattering angles from $\Theta = 120°$ to $150°$ for $\theta_0 = 60°$ are less influenced by multiple scattering than the principal plane radiances. The retrieved values of ω_0 for the results presented in Figure 1 (both wavelengths) were all excellent, the error being $\lesssim 0.1\%$.

In the case of the Urban model, for which the phase function has no rainbow feature and is not as sharply peaked in the forward direction, the retrievals were better than those in Figures 1 and 2. Also, the value of ω_0 was retrieved with an error $< 0.1\%$.

Measurment of the radiance in the aureole region of the almucantar with $\phi = 1°$ is difficult; however, Nakajima et al.,[5] have reported aureole measurements down to $\phi = 2°$. Thus, we have performed computations similar to those described above, but with a minimum value of 2° for ϕ in the almucantar rather than 1°. For the Urban model at both 412 and 865 nm and the Maritime model at 865 nm, the results were essentially unchanged from the previous computations for both $\tau_a = 0.2$ and 2.0. However, for the Maritime model at 412 nm, the retrievals of both ω_0 and P were degraded (errors $\sim 10 - 20\%$ in P for $\Theta \gtrsim 100° - 110°$). This appears to be due to the fact that the Maritime model's phase function at 412 nm is so strongly peaked in the forward direction (the most so of all of the models used here), and suggests that in such cases the radiance probably cannot be inverted accurately to provide optical properties without having small-angle radiance data.

4. Concluding remarks

To our knowledge, the results presented here represent the first inversion of the boundary radiances emerging from an optically thick (multiply scattering) medium to obtain its basic optical properties — ω_0 and $P(\Theta)$. We believe that the results demonstrate that the retrieval method holds significant promise for combining aircraft (or satellite) and surface data to study the columnar optical properties of aerosols over oceans or over large lakes. As such, we are performing a complete sensitivity analysis to try to understand the limitations of the method. This analysis includes sensitivity to radiometric calibration errors, variations in aerosol type with altitude, the horizontal spatial variations in aerosol properties, the influence of polarization, aircraft altitude, etc. The results of this study, which is now underway, will be presented in a later paper.

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Figure Captions

Figure 1. Comparison between the true $\omega_0 P(\Theta)$ (solid line) and the retrieved $\omega_0 P(\Theta)$ (circles) for the Maritime aerosol model with RH = 99% and $\theta_0 = 60°$: (a) 412 nm; (b) 865 nm. Lower curves are for $\tau_a = 0.2$, upper curves for $\tau_a = 2.0$. Values for $\tau_a = 2.0$ are $\times 10$.

Figure 2. % Error in $\omega_0 P(\Theta)$ for $\tau_a = 0.2$ (dashed line) and $\tau_a = 2.0$ (solid line): (a) 412 nm; (b) 865 nm.

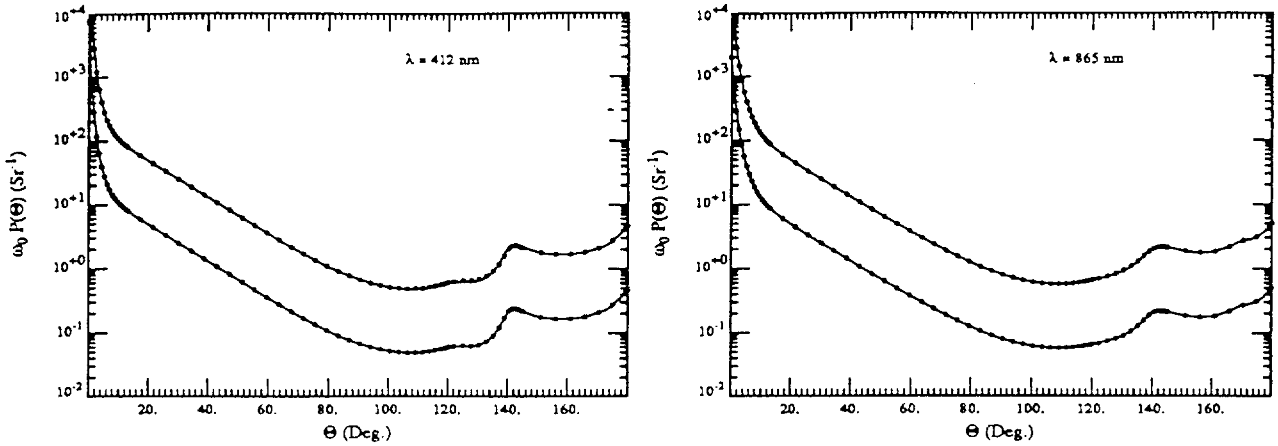

Figure 1a. Figure 1b.

Figure 1. Comparison between the true $\omega_0 P(\Theta)$ (solid line) and the retrieved $\omega_0 P(\Theta)$ (circles) for the Maritime aerosol model with RH = 99% and $\theta_0 = 60°$: (a) 412 nm; (b) 865 nm. Lower curves are for $\tau_a = 0.2$, upper curves for $\tau_a = 2.0$. Values for $\tau_a = 2.0$ are $\times 10$.

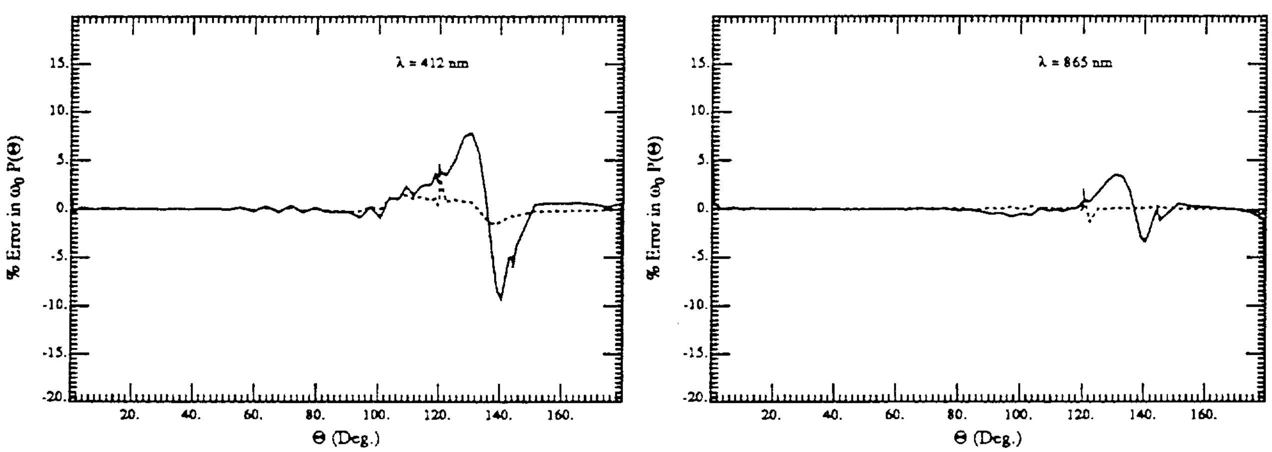

Figure 2a. Figure 2b.

Figure 2. % Error in $\omega_0 P(\Theta)$ for $\tau_a = 0.2$ (dashed line) and $\tau_a = 2.0$ (solid line): (a) 412 nm; (b) 865 nm.